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HURRICANE BERTHA: RADAR-GAUGE COMPARISONS AND CHANGING THE Z-R RELATIONSHIP

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1. INTRODUCTION

On July 12, 1996, the WSR-88D located at the National Weather Service (NWS) office in Newport, North Carolina, provided close-up observations of Hurricane Bertha as it tracked across eastern North Carolina. The eye of Bertha passed within 40 nm of the Radar Data Acquisition (RDA), producing widespread heavy rain and flooding over the region. Since Bertha's path was in close proximity to the RDA, it was possible to compare data from 48 rain gauges within the 124 nm Newport WSR-88D umbrella of coverage to Storm Total Precipitation (STP) estimates from the radar.

Previous local studies involving radar-gauge comparisons during tropical rains have been carried out by NWS personnel at the Newport office. During Hurricane Gordon in November 1994, it was found that WSR-88D rainfall estimates were underestimated by 50 to 70 percent (Thacker 1996). Another study by Choy et al. (1996) from the NWS office in Melbourne, Florida, indicated considerable underestimation of rainfall during tropical rains. At that time, NWS operational personnel were not allowed to change the Z-R relationship during tropical events.

During Hurricane Bertha, the Z-R relationship was changed and rainfall estimates from the radar were obtained for the entire time that tropical rains affected eastern North Carolina. The focus of this paper is to examine radar performance based on the modified Z-R relationship. Parameters such as mean radar bias and average difference were evaluated to provide an objective view of how the radar performed during this tropical event.

2. BACKGROUND

The Newport WSR-88D RDA and Radar Products Generator (RPG) are located along the central coast of North Carolina approximately 9 nm west-northwest of Morehead City (Fig.1). WSR-88D radars overlapping Newport's umbrella of coverage are located in Wakefield, VA (KAKQ) to the north, Raleigh, NC (KRAX) to the west, and Wilmington, NC (KLTX) to the south.

3. LIMITATIONS TO RADAR MEASURED RAINFALL

There are many factors that can cause error in radar rainfall estimates. Reflectivity factor errors can arise from hardware calibration, beam blockage by objects close to the radar, anomalous propagation of the beam, and attenuation by a wet radome. Evaporation and advection of precipitation before it reaches the ground are other possible sources of error. For example, agreement between radar and gauge reports generally decreases with increasing radar range (Wilson 1976; Brandes and Sirmans 1976). This is likely due to an increasing sampling volume and the height of the beam above the ground at far ranges leads to a higher probability that precipitation echoes aloft are much different from those near the ground. Another important error source is variations in the drop-size distribution and the impact of vertical air motions. There are many studies indicating errors that can occur when trying to estimate rainfall from radar. A summary of these error sources can be found in Wilson and Brandes (1979).

Even though radar measured rainfall is not perfect, it is a useful tool that can alert forecasters to where heavy rain is likely falling and help indicate locations where there is the potential for flooding. Future plans call for a calibration of the radar with the implementation of a Kalman filter. This Gage Data Support System (GDSS) would be used to calculate an hourly multiplicative bias between real-time gauge measurements and radar precipitation estimates.

4. WSR-88D PRECIPITATION PROCESSING AND THE Z-R RELATIONSHIP

Radar does not measure rainfall rate directly; instead, it measures the backscattered energy from precipitation particles. The WSR-88D precipitation processing subsystem is complex. Numerous quality control steps are used to prepare reflectivity factor data for input into the precipitation rate algorithm. Subsequently, another set of complex tests are done before receiving a final output. Within this precipitation processing subsystem a hybrid scan technique is used to obtain reflectivity sample volumes (Fig.2). The hybrid scan technique uses higher angles close to the radar and lower angles as distance increases from the radar to ensure a nearly uniform sampling height above the surface. A process called bi-scan maximization is used beyond 27 nm from the RDA. This process selects the maximum reflectivity value from the 0.5 degree and 1.5 degree slices. If ground clutter is present, the sample volume from the 1.5 degree elevation angle is used, thus reducing the effect of ground clutter contamination. The radar also has adaptable thresholds to minimize the effects of weak reflectivity returns and overestimation of rainfall due to hail contamination. These thresholds are 18 dBZ and 53 dBZ, respectively. This means that rainfall is not computed with values below 18 dBZ, and all reflectivities greater than 53 dBZ are truncated to reflect rainfall rates at that value. Since hail is rare in tropical rain events, the truncation of reflectivities above 53 dBZ may be a source of underestimation error.

The WSR-88D precipitation rate algorithm computes rainfall rates from the Z-R relationship. The default Z-R relationship is $Z=300R^{1.4}$, where Z is the base reflectivity from the sectorized hybrid scan. The final output, R, is a rainfall rate for each sample volume.

During Hurricane Bertha we changed the Z-R relationship to $Z=250R^{1.2}$. The smaller coefficient and smaller exponent likely make this relationship a better one in tropical conditions, especially for heavy rainfall rates. For example, if a rainfall rate of 25mm/hr is substituted for R in the default Z-R relationship, Z=44.3 dBZ. In the modified Z-R relationship, Z=40.8 dBZ. A rainfall rate of 100mm/hr would produce Z=52.7 dBZ for the default relationship and Z=47.9 dBZ for the new Z-R relationship. The new Z-R relationship is more efficient because it takes lower dBZ values to produce the same rainfall rates. In tropical rains drop-sizes are usually much smaller, which means reflectivity values are usually lower. This particular Z-R relationship is used to account for this phenomena. This does not solve the problem entirely because similar storms in the same geographic area can be associated with a wide range of Z-R relationships. These variations reflect the predominance of one or another physical processes that influence drop-size distribution (Atlas and Chmela 1957; Srivastava 1971; Gunn and Marshall 1955).

5. THE Z-R CHANGE AND RAIN GAUGE DATA

The Z-R relationship was changed on Thursday, July 11, at 2148 UTC. Only a few very light showers had fallen up to this point so continuity between the STP product and the rain gauge data was maintained. At this point, Hurricane Bertha was still well to the south but its large tropical circulation was beginning to impinge on the region with more concentrated showers advancing onshore.

The 48 rainfall reports were gathered from various sources such as local airports, NWS cooperative observers, NWS personnel and trained spotters. The local airports and cooperative observers measured rainfall by using standard 8 inch rain gauges. Weather Service personnel and trained spotters used a variety of different rain gauges ranging from the standard 8 inch gauge to the smaller 4 inch diameter gauges with 11 inch capacity.

6. METHODOLOGY

Data from the 48 rain gauges were compared to STP totals (Fig. 3) for the 30 hour period from 2148 UTC July 11 to 0332 UTC July 13. The WSR-88D HYPROD.DAT file could not be copied for this event. This particular file produces output that allows access to the precise radar estimated rainfall. Despite the absence of this file, the Operational Support Facility (OSF) suggested that statistical integrity could still be maintained by using mid-point values between each STP threshold. For example, if the STP bin used had an estimate of 2.50 inches, it was recorded as 2.75 inches, the mid-point between 2.50 and 3.00 inches on the STP accumulation legend.

It should be noted that there is a fundamental difference in precipitation measuring methods between the rain gauge network and the WSR-88D. The WSR-88D calculates areal average precipitation estimates over areas of 2 km by 2 km, while the rain gauge network directly measures precipitation for a point. The point rainfall observations may not be fully representative of the WSR-88D areal precipitation estimates as interpolated to a point.

Noting the differences between the observing systems, a comparison was made between the gauge and the STP bin nearly over the gauge. This particular comparison was called *closest bin*. Two other comparisons were made which involved centering the gauge in an array of nine STP bins. The second comparison examined how the gauge amounts related to the average of the nine STP bins. This was called *average bin*. The third compared the gauge to whatever STP bin in the 9-bin array most closely resembled the gauge amount. This was called *best bin*. The best bin technique is similar to what the WSR-88D precipitation processing algorithms will do in the future. Once real-time rain gauges are incorporated, the precipitation processing algorithms will compare the gauge amount to the best bin in an array centered on the gauge. A multiplicative bias will then be computed hourly.

Mean radar bias, average difference, and adjusted average difference (Fig 4) were calculated for closest bin, average bin and best bin. The calculations were made for all ranges within the 124 nm Newport WSR-88D umbrella of coverage. Since 90 percent of the Newport County Warning Area (CWA) is within 75 nm of the radar, computations were also done for this area to examine how the radar performed at close to medium ranges. Finally, calculations were carried out for the longer ranges (75-124 nm) from the RDA to see how the radar bias varied further from the RDA, where the beam height was likely overshooting the heavy rain cores.

7. RESULTS

Results of the analysis for all 48 gauges are indicated in Table 1. The mean radar bias for closest bin was 1.47 with an average difference of 29.4 percent. A perfect bias is 1.00, a bias over 1.00 means the radar underestimated rainfall amounts while a bias under 1.00 signifies overestimation. The mean radar bias of 1.47 and the average difference of 29.4 percent represent an objective view of how the radar performed. The WSR-88D precipitation processing algorithms underestimated rainfall amounts as compared to gauge reports. After the mean radar bias was applied, the average difference dropped to 24.5 percent. The best bin technique exhibited better performance in estimating rainfall amounts with a bias of only 1.3 and an average difference of 21.3 percent. When the bias was applied the average difference improved to 20.4 percent.

Computations were also done for 29 gauges that were within the Newport CWA (Table 2). As mentioned earlier, the Newport CWA is relatively small with 90 percent of the area within 75 nm of the radar. The results represent an objective view of how the radar performed at the close and medium ranges. The mean radar bias using the closest bin was 1.38 with an improvement to 1.23 when the best bin technique was applied. After the mean radar bias was applied, the average difference of all 3 parameters improved considerably.

Nineteen gauges were used for computations at the longer ranges. Results for the longer ranges did not exhibit as much skill with average differences between 26 and 37 percent (Table 3). This is reasonable given the beam height at 0.5 degrees ranges from 8,000 feet to 17,000 feet from 75 nm to 124 nm away. The height of the beam at longer ranges likely overshoots the heavy rain cores, especially in tropical situations where the highest reflectivities are usually located at lower altitudes. After the mean radar bias was applied, the average difference improved considerably.

8. DISCUSSION AND CONCLUSION

The Z-R relationship was changed as Hurricane Bertha approached and then moved onshore over eastern North Carolina. Results for all ranges (0-124 nm) indicated that the radar underestimated rainfall amounts by 29.4 percent. When a multiplicative bias was applied the average difference dropped to 24.5 percent. The best bin technique had better average and adjusted average differences and yielded rainfall estimates, which differed from the rain gauge measurements by about 20 percent.

The radar exhibited the most skill at the close to medium ranges (0-75 nm). The best bin technique yielded an average difference of only 18.2 percent. As far as the Newport CWA was concerned, the radar performance with the new Z-R relationship was quite respectable.

At the longer ranges, underestimation was more pronounced, likely because the higher beam height was overshooting the heavy rain cores. Forecasters need to be aware of the tendency for significant underestimation at the longer ranges. In the future, a larger bias and perhaps even a different Z-R relationship will be needed for locations beyond 75 nm from the RDA. It should be noted that after applying the multiplicative bias the average difference did improve substantially.

Results from the new Z-R relationship are far better than results from Hurricane Gordon in November of 1994, when the default Z-R relationship was used and average differences were on the order of 50 to 70 percent. Choy et al. (1996) did an extensive gauge-radar comparison on Tropical Storm Gordon as it affected central Florida for a 72 hour period in November, 1994. The Z-R relationship in their study was not changed. They calculated a *center bin* which was the same as closest bin in this study. The average difference for the entire 124 nm umbrella was 46 percent compared to 29 percent for this study. It should be noted that there are differences between the two studies. The Melbourne study had access to the HYPROD.DAT file, so exact radar estimated precipitation values were known. In this study we had to use mid-point values. The Melbourne study also had more rain gauges for comparison, a longer period of rain, and a higher percentage of gauge locations further from the RDA.

Operationally, it is important to conduct studies such as this and the one by the Melbourne office. During the next tropical event that affects eastern North Carolina, forecasters could very quickly apply a multiplicative bias to come up with an estimated rainfall amount. The estimate does not have to be perfect; an approximate will allow forecasters to make an educated decision as to how much rain a particular location is receiving.

Since Archive Level II data was unavailable for this study, it is impossible to conclusively state that the modified Z-R relationship drastically outperformed the default relationship. This study indicates that the modified Z-R relationship most likely produced radar estimated rainfall amounts that were more accurate than the default relationship. Through the use of Archive Level II data more information will be available to evaluate future storms. Perhaps a slightly different Z-R relationship re-run using Archive II data would have produced better results. Further study is definitely warranted and with the future addition of the Gage Data Support System, better results are entirely possible. Given its high frequency of tropical systems, coastal North Carolina will remain an excellent area for research in this regard.

9. ACKNOWLEDGMENTS

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Table 1. Results of closest, average and best bin for all ranges (48 gauges, 0-124 nm).

Parameter	Closest Bin	Average Bin	Best Bin
Mean Radar Bias (Eq. 1)	1.47	1.49	1.30
Average Difference (Eq. 2)	29.4%	30.7%	21.3%
Adjusted Average Difference (Eq. 3)	24.5%	26.8%	20.4%

Table 2. Results of closest, average and best bin for MHX CWA (29 gauges, 0-75 nm).

Parameter	Closest Bin	Average Bin	Best Bin
Mean Radar Bias (Eq. 1)	1.38	1.36	1.23
Average Difference (Eq. 2)	25.7%	26.6%	18.2%
Adjusted Average Difference (Eq. 3)	23.5%	24.6%	17.6%

Table 3. Results of closest, average and best bin for longer ranges (19 gauges, 75-124 nm).

Parameter	Closest Bin	Average Bin	Best Bin
Mean Radar Bias (Eq. 1)	1.61	1.66	1.36
Average Difference (Eq. 2)	34.9%	37.0%	25.9%
Adjusted Average Difference (Eq. 3)	22.2%	25.6%	21.5%

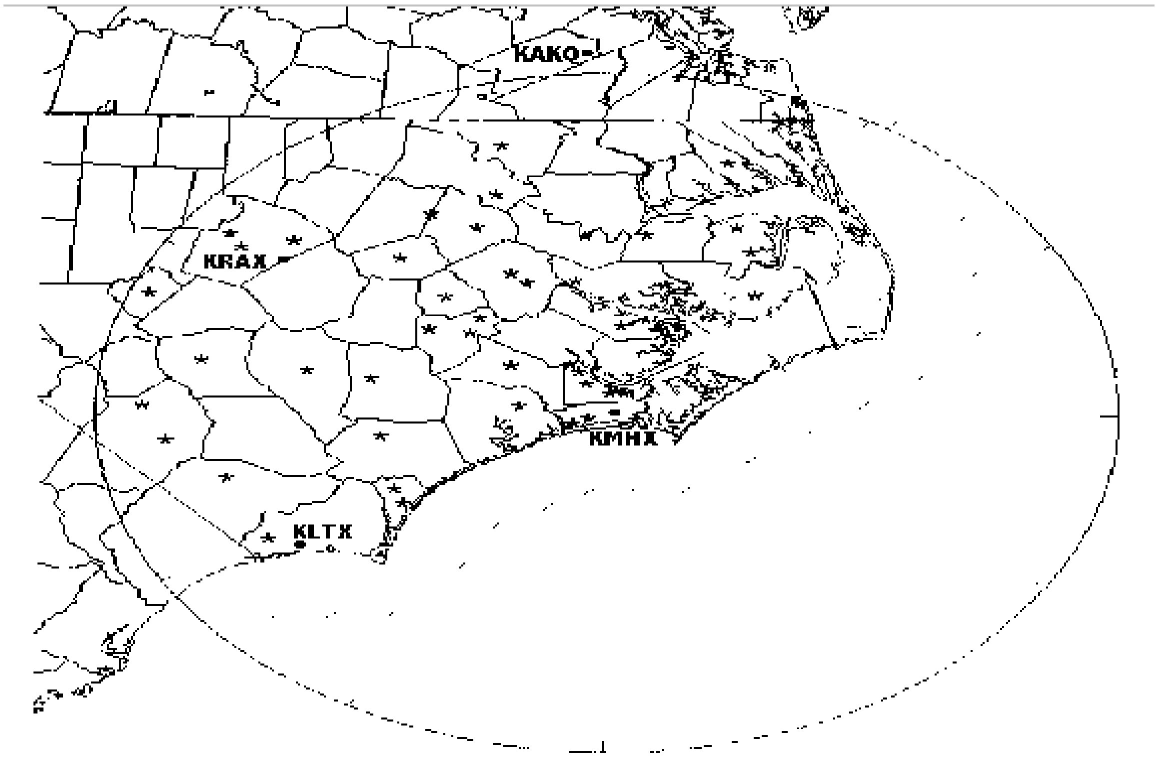

Figure 1. Map of Eastern North Carolina. The range ring defines the 124 nm area of WSR-88D rainfall estimation with rain gauge locations indicated by the asterisk (*).

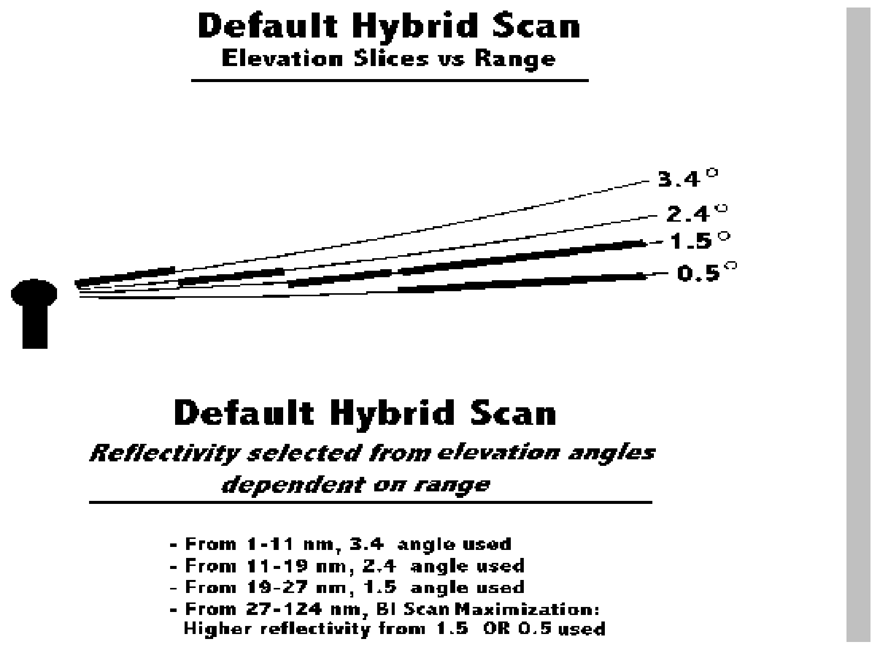

Figure 2. The WSR-88D Hybrid Scan Strategy (Federal Meteorological Handbook (1991)) uses different elevation slices versus range to maintain a nearly uniform sampling height above the surface.

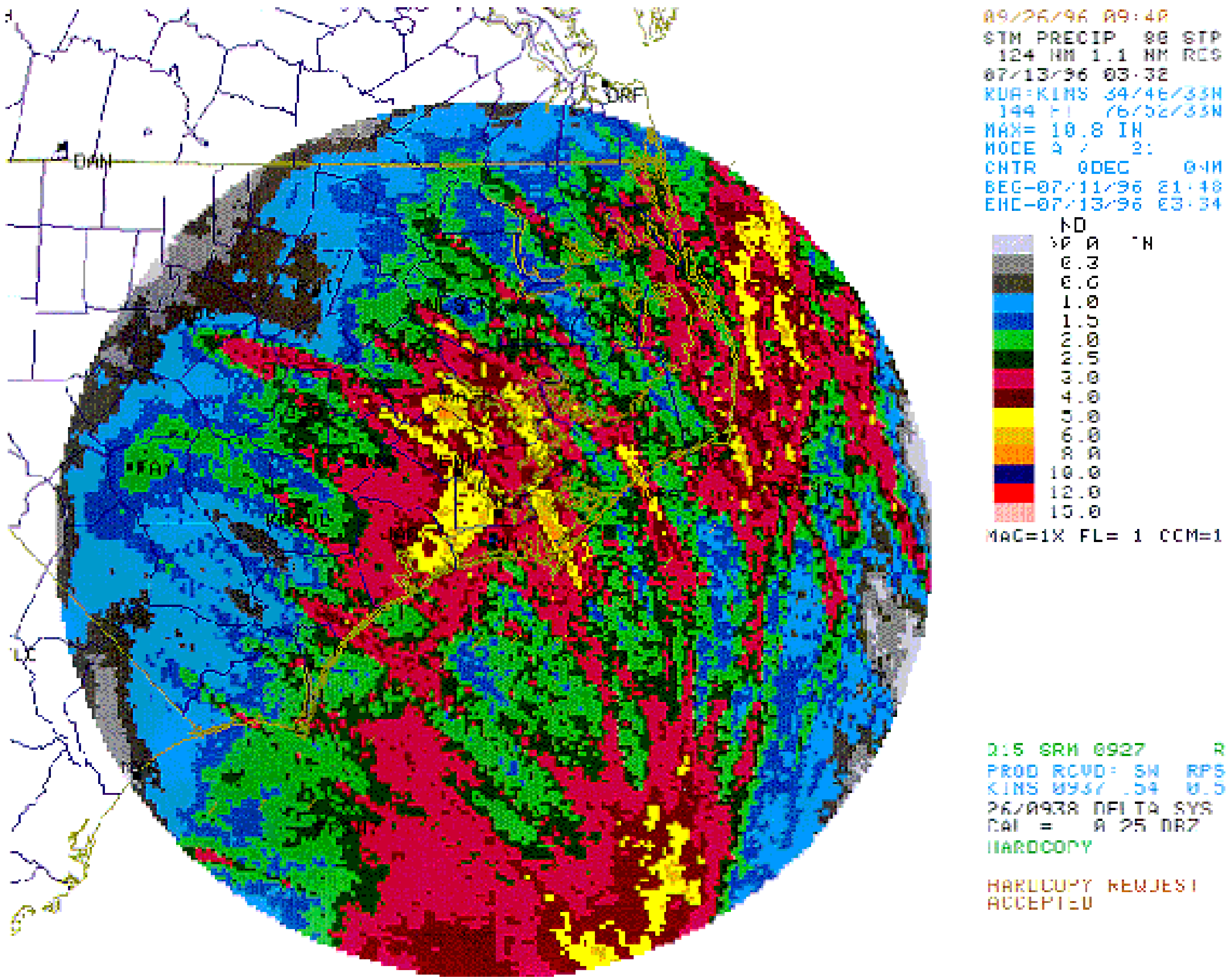

Figure 3. The Storm Total Precipitation (STP) product from the KMHX WSR-88D radar from2148 UTC on July 11, 1996, to 0334 UTC on July 13, 1996. Mid-point values were used for radar precipitation estimates.

Mean Radar Bias (Eq. 1) = $\frac{1}{N}\sum_{1}^{N} \frac{G_i}{R_i}$

Average Difference (Eq. 2) = $\frac{1}{N}\sum_{1}^{N} |(G_i - R_i)/G_i| * 100\%$

Adjusted Average Difference (Eq.3) = $\frac{1}{N}\sum_{1}^{N} |(G_i - (\overline{G/R})R_i)/G_i| * 100\%$

Figure 4. Equations used to evaluate the modified Z-R relationship. For all equations, (G) is the gauge total and (R) is the radar STP total. The Adjusted Average Difference (Eq 3) is calculated applying the mean radar bias.